

X-ray diffraction studies of 145 MeV proton-irradiated AlBeMet 162



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ABSTRACT

AlBeMet 162 (Materion Co., formerly Brush Wellman) has been irradiated with 145 MeV protons up to $1.2 \times 10^{20} \text{ cm}^{-2}$ fluence, with irradiation temperatures in the range of 100–220 °C. Macroscopic post-irradiation evaluation on the evolution of mechanical and thermal properties was integrated with a comprehensive X-ray diffraction study using high-energy monochromatic and polychromatic X-ray beams, which offered a microscopic view of the irradiation damage effects on AlBeMet. The study confirmed the stability of the metal–matrix composite, its resistance to proton damage, and the continuing separation of the two distinct phases, *fcc* aluminum and *hcp* beryllium, following irradiation. Furthermore, based on the absence of inter-planar distance change during proton irradiation, it was confirmed that the stacking faults and clusters on the Al (1 1 1) planes are stable, and thus can migrate from the cascade region and be absorbed at various sinks. XRD analysis of the unirradiated AlBeMet 162 showed clear change in the texture of the *fcc* phase with orientation especially in the Al (1 1 1) reflection which exhibits a “non-perfect” six-fold symmetry, implying lack of isotropy in the composite.

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1. Introduction

AlBeMet, an aluminum–beryllium compound with high Be content, is better described as a metal–matrix composite rather than an alloy, since the two metals remain as separate phases. The AlBeMet metal–matrix composite consists of 62% by weight beryllium with the balance in 1100-series aluminum [1–3]. AlBeMet exhibits desirable physio-mechanical properties such as low density (2.1–2.3 g/cc), high specific stiffness, high thermal conductivity and high mechanical isotropy [1–6].

Because of the high beryllium content and the fact that the two constituent metals, beryllium and aluminum, remain as separate phases, AlBeMet is expected (same as beryllium) to also exhibit excellent neutron multiplication and moderation properties. Beryllium is under consideration for use as plasma facing material in fusion reactors as well as an effective neutron reflector in fission reactors [7]. Its relatively low thermal-neutron-absorption cross section makes it desirable for cold-source reactor reflectors, but long-term exposure to neutrons (or to energetic protons) may result in gradual buildup of transmutation gases such as ⁴He and

³H, which may, above a threshold dose or operating temperature, lead to swelling and degradation in its mechanical properties. These irradiation-generated transmutation gases exhibit low solubility, leading to supersaturation of the beryllium matrix and to eventual precipitation into bubbles that coalesce, inducing swelling and embrittlement.

AlBeMet is considered as a cooled substrate to the grazing incidence metal mirror (GIMM) [8,9] that is part of the final optics that transport the laser beams to the reaction chamber center in Inertial Fusion Power Reactors. The primary objective is to utilize a material structure that is resistant to neutron swelling. Dielectric mirrors for reflecting 248 nm laser wavelengths were irradiated at ~175 °C to doses up to $0.1 \times 10^{25} \text{ n/m}^2$ ($E > 0.1 \text{ MeV}$.) Substrate materials such as SiC, AlBeMet-162 and Al-6061 were evaluated based on resulting flux values at the dielectric mirrors. The potential applicability of AlBeMet in fusion reactors as an interfacial material between beryllium and copper has been explored [10] to provide diffusion bonding. Irradiation effects in single crystal aluminum from 1 MeV protons and flux $\sim 10^{18} \text{ proton/cm}^2$ per 1.5×10^4 at room temperature were studied [11] via diffractometric techniques. Effects of fast neutron fluence ($E > 1 \text{ MeV}$) up to $4.67 \times 10^{22} \text{ n/cm}^2$ on beryllium has been studied [12] and in particular helium accumulation in the matrix.

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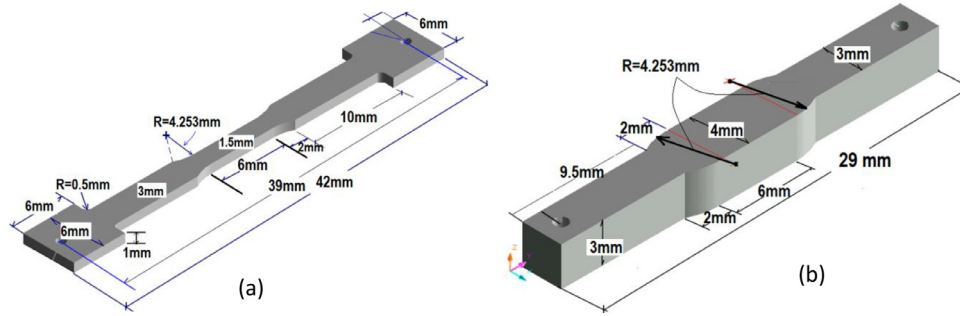


Fig. 1. Shape and dimensional details of the two types of specimens utilized in the proton irradiation of beryllium study (a) tensile, and (b) CTE specimens.

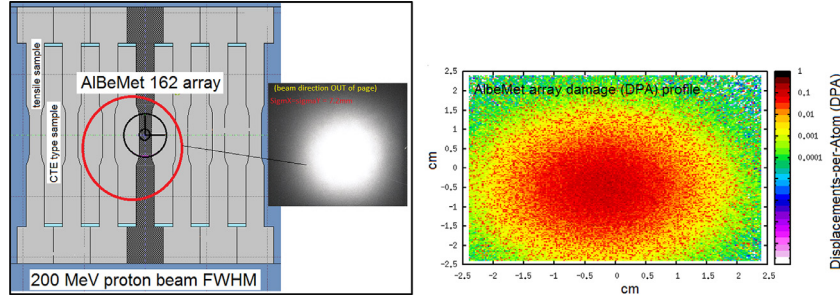


Fig. 2. AlBeMet array configuration normal to the incident proton beam (left) including the exposed nickel foil used to determine proton beam shape and position relative to samples. Estimated damage in DPA using the transport code FLUKA (right).

In particle accelerators, AlBeMet has enjoyed use as vacuum windows for intense particle beams, and is being considered (by author KTM) as a low-Z pion-producing spallation target for multi-MW-power, next-generation accelerator concepts. AlBeMet has successfully been introduced in the 200 MeV proton beam extraction beamline of the BNL isotope production facility [13] in place of a vacuum beryllium window and has exhibited excellent performance and survivability after receiving an integrated fluence $>10^{22}$ p/cm². AlBeMet 162 has been considered in a similar 100 MeV linear accelerator [14] for 20 MeV and 100 MeV user facilities of the Proton Engineering Frontier Project (PEFP) prompted by the need for a window material with sound mechanical properties at high temperatures and capable of withstanding the atmospheric pressure applied to large-sized window.

In spite the above-mentioned scientific interest in AlBeMet, very few studies have been performed that would reveal the interworking of the two component phases under extreme conditions, such as high temperature, high-flux neutron or proton irradiation, etc. In the present study AlBeMet 162 (Brush Wellman) that has been irradiated with 145 MeV protons from the Brookhaven National Laboratory (BNL) Linac to a peak fluence of 1.2×10^{20} /cm² fluence and irradiation temperatures in the range of 100–200 °C has been studied using X-ray diffraction techniques at the BNL NSLS synchrotron and high energy monochromatic and white beam X-rays. The paper focuses on the effects of energetic protons on the microstructure of AlBeMet using the X-ray techniques and attempts to link microscopic observations with macroscopically observed effects of stress-strain behavior, ductility loss and thermal stability.

X-ray diffraction studies focusing on the effects of irradiation and macroscopic stress on the microstructural evolution and crystallographic role in the deformation of AlBeMet were also conducted as part of the experimental campaign. Two X-ray diffraction experiments were performed on AlBeMet 162. The first of the experiments utilized the 70 keV monochromatic X-rays at the X17A beamline of NSLS to study the unirradiated, as received material and explore its phase map as well as crystallographic struc-

ture achieved in developing the binary matrix composite as well as texture characteristics (*i.e.* anisotropy). The second experiment utilized the 200 keV polychromatic X-rays at the X17B1 beamline of NSLS and the EDXRD technique to study the effects of proton irradiation on AlBeMet 162. The objective of these X-ray diffraction analyses was to (a) confirm that the material is a matrix composite with separate phases (binary) and not an alloy and (b) that following irradiation the composite nature is maintained, (c) what crystallographic changes, if any, occur as a result of energetic proton irradiation (shifting, broadening, appearance of other phases, etc.).

Further, and prompted by microstructural changes observed in irradiated beryllium where transmutation gases are generated from the interaction of energetic protons with the lattice, a closer look into the evolution of the AlBeMet 162 microstructure is given. Transmutation gases in beryllium exhibit low solubility which results in super-saturation of the matrix [12] eventually precipitating into helium bubbles that coalesce and induce swelling. To assess whether similar processes are occurring, X-ray diffraction changes and macroscopic thermo-physical analysis data of irradiated AlBeMet are analyzed.

The study confirmed the stability of the metal matrix composite and its resistance to proton induced damage and the continuing separation of the two distinct phases, *fcc* aluminum and *hcp* beryllium, following irradiation. The analysis also confirmed, based on EDXRD data which verified the absence of crystallographic plane distance changes during proton irradiation of specific plane orientations of the *fcc* phase. Specifically, stacking faults and clusters on the Al (1 1 1) planes, expected to be stable and thus prone to migration from the cascade region and eventual absorption at various available sinks (dislocations, grain boundaries), appear to be mobile as expected during the proton irradiation explained by the fact that there appears to be no change in the (1 1 1) plane distance of the *fcc* phase.

An in-depth XRD analysis focusing on the symmetry and texture of unirradiated AlBeMet 162 revealed change in the texture of the *fcc* phase with orientation of a number of crystallographic plane reflections a variation more pronounced in the Al (1 1 1)

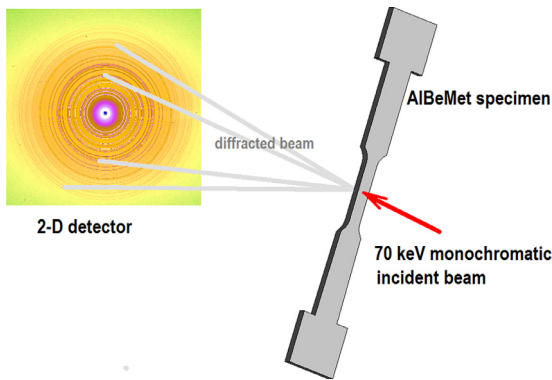


Fig. 3. XRD experiment configuration utilized on AlBeMet 162 tensile-type samples at X17A beamline.

reflection which exhibits a “*non-perfect*” six-fold symmetry implying lack of isotropy in the composite. This finding appears to contradict manufacturer’s assertion of achieved high isotropy in the composite.

2. Experimental methods

2.1. Irradiation experiment

An array of AlBeMet 162 specimens consisting of two types of geometry as shown in Fig. 1 was formed into a special capsule and along with a number of other test materials shown in Fig. 2 were placed in the path of 200 MeV protons of the Brookhaven National Laboratory Linac. The total flux of protons incident on the integrated array and also the AlBeMet capsule sample was $\sim 5.27 \times 10^{20}$ (integrated beam current $\sim 23,453 \mu\text{A h}$). The proton energy at the location of the AlBeMet capsule was in the range 142–145 MeV following beam energy degradation from the Linac 200 MeV energy by a series of upstream target layers placed in the path of the proton beam (Vascomax, Ti6Al4V, Gum metal, etc.). Impinging protons on the upstream face of the AlBeMet array samples penetrated through the thickness of the array along the proton beam loosing ~ 2.8 MeV of energy. Layers of research targets and isotope producing targets downstream of the AlBeMet array consumed the remaining 142 MeV of the proton beam.

The incident proton beam had a Gaussian transverse profile with $\sigma_x = \sigma_y = 7.2$ mm and a 5 mm x - y offset from the center of the array. Special nickel foils integrated into the irradiation assembly were analyzed and helped establish the beam spot size, shape and position during irradiation. Fig. 2 depicts a cross section of the AlBeMet array, as it was modeled into the neutronics code FLUKA that was implemented to assess the energy deposition and thus the irradiation temperature using high fidelity finite element based numerical analysis. Shown in Fig. 3 is the special nickel foil image exposed for two minutes in the proton beam and analyzed to help establish the shape and position of the beam. Fig. 2(b) depicts the estimated damage in Displacements-per-Atom (DPA) estimated using the FLUKA neutronics code [15,16]. DPA values for the two phases (aluminum and beryllium) were estimated for the irradiation conditions using the FLUKA code. Specifically, for the beryllium phase the peak damage was ~ 0.01 DPA and 0.044 DPA for aluminum.

2.2. Macroscopic post-irradiation analysis

To assess the macroscopic behavior of AlBeMet 162 and the effects of proton irradiation on its physical properties, two types of PIE experiments were conducted namely tensile test/fracture anal-

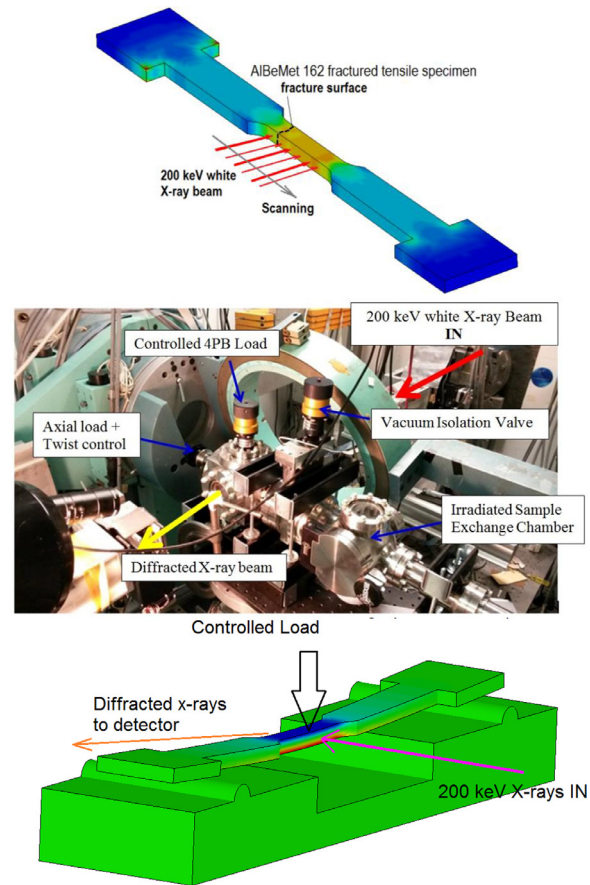


Fig. 4. EDXRD experimental stage utilized on AlBeMet 162 tensile-type samples at X17B1 beamline.

ysis and thermal cyclic analysis. Specifically, by utilizing a Tenius-Olsen 5000 kN tensile testing system inside the hot cell facility at Brookhaven National Laboratory, the proton irradiated tensile specimens shown in Figs. 1 and 2 were tested in tension to fracture remotely at room temperature. No extensometer was used over the specimen gage. To assess the proton irradiation effects on the stress-strain behavior and ductility loss, unirradiated samples were tested under the exact same conditions. Primary objective of the macroscopic stress-strain analysis was observe the resistance to ductility loss of this matrix composite and to link potential macroscopic features of the stress-strain curve to the crystallographic deformation mechanisms of the individual components (*hcp* beryllium and *fcc* aluminum).

Thermal cyclic analysis using a LINSEIS high sensitivity (nm-level) horizontal dilatometer (dual quartz rod) was performed on the CTE-type samples shown in Figs. 1 and 2. Thermal cycles to 300 °C followed by thermal cycles to 610 °C were conducted to assess the effect of proton irradiation on the linear thermal expansion and the role of thermal annealing in reversing the induced damage which is expected in the form of lattice swelling stemming from interstitial and vacancy generation as well as transmutation ^4He and ^3H gasses. Part of the thermal analysis objective was the observation of the evolution of the thermal expansion coefficient and the thermal dimensional stability of AlBeMet 162.

2.3. X-ray diffraction experiments

Two types of X-ray diffraction experiments were conducted using high energy X-rays at the Brookhaven National Synchrotron (NSLS). Specifically, 70 keV monochromatic X-rays of the X17A

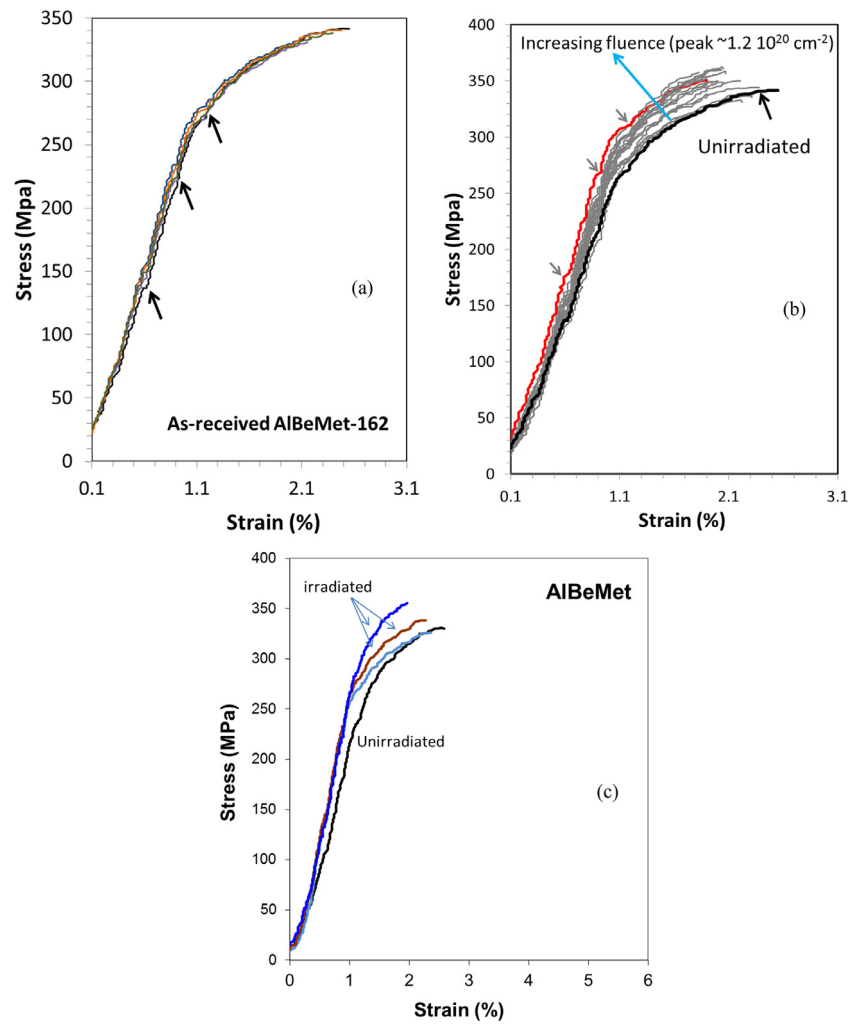


Fig. 5. Effects of proton irradiation on the stress–strain behavior of AlBeMet 162. (a) Unirradiated, as-received material indicating stable microstructure from reproducibility of data, (b) ductility loss with irradiation proton fluence, (c) effects of proton irradiation on elastic modulus.

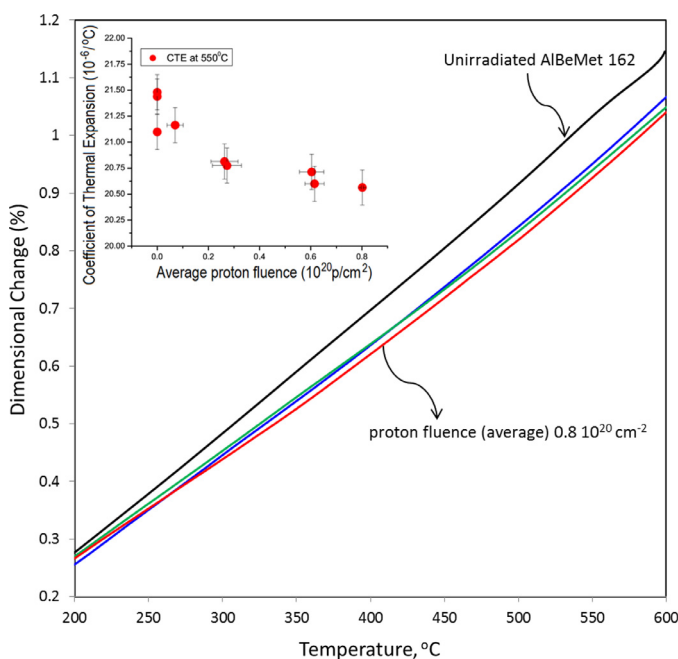


Fig. 6. Proton irradiation effects on dimensional change and CTE of AlBeMet 162.

beamline (see Fig. 3(a)) were used on unirradiated AlBeMet 162 sample to establish the microstructural state and the phase delineation in the as-received material. In addition, this XRD study aimed to validate the isotropy that characterizes this binary matrix composite and to explore the presence of residual grain strain that stems from its fabrication technique.

Energy Dispersive X-ray Diffraction (EDXRD) experiments were performed utilizing the 200 keV polychromatic beam at the X17B1 beamline at NSLS. In these experiments, the proton irradiation effects on the crystal structure of previously mechanically tested/fractured AlBeMet 162 specimens were studied by studying the crystallographic evolution and micro-strains over the specimen gage which, based on the irradiation conditions and in particular the Gaussian shape of the irradiating (proton) beam, was exposed to a varying fluence over the 10 mm gage length. In addition, lattice deformation mechanisms characteristic of the crystal structure of the constituent metals (Be and Al) were expected to be mobilized within the gage that prior to fracture has deformed plastically. The schematic shown in Fig. 3(b) depicts the EDXRD approach on irradiated/fractured AlBeMet 162 specimens. In addition, unirradiated, as-received AlBeMet 162 samples were analyzed using EDXRD with scanning across the thickness of the specimen at the mid-span to compare with irradiated data over the same scanning path.

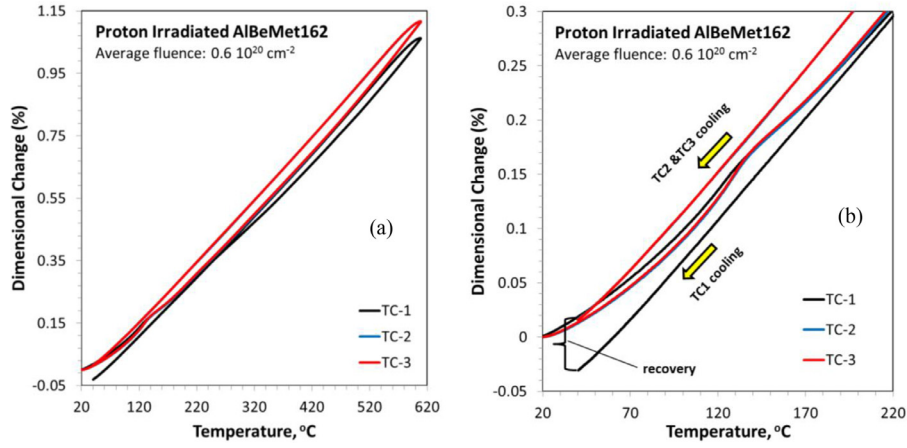


Fig. 7. Thermal annealing of irradiation damage in AlBeMet 162 observed with swelling recovery.

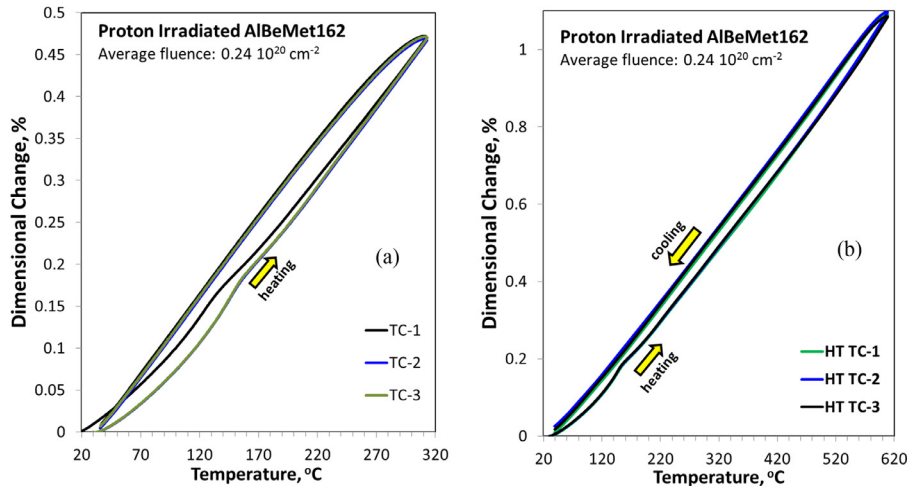


Fig. 8. Dimensional stability of proton irradiated AlBeMet 162 through low and high temperature thermal cycling.

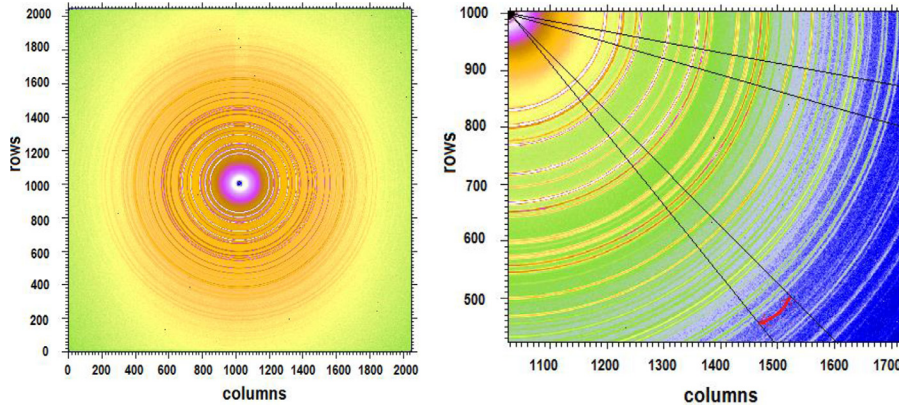


Fig. 9. Diffraction pattern of unirradiated AlBeMet 162 obtained by a 2-D detector using 70 keV monochromatic X-rays at NSLS X17A beamline.

3. Results

3.1. Macroscopic post-irradiation evaluation

Macroscopic stress-strain results obtained following proton irradiation and prior to the X-ray diffraction experiments at NSLS are shown in Fig. 5(a–c). Fig. 5(a) depicts the stress-strain behavior of unirradiated, as received AlBeMet 162 samples. Several ten-

sile tests to fracture we conducted to establish both the baseline and also observe potential scattering of the data due to the metal matrix composite structure of the material. The mechanical tests on unirradiated AlBeMet 162 revealed that the stress-strain behavior of the material is reproducible with very little scattering. Also noted (shown with arrows) is the reproducible presence of deformation “kinks” which represent plastic deformation zones that are attributed to be triggered by lattice deformation mechanisms

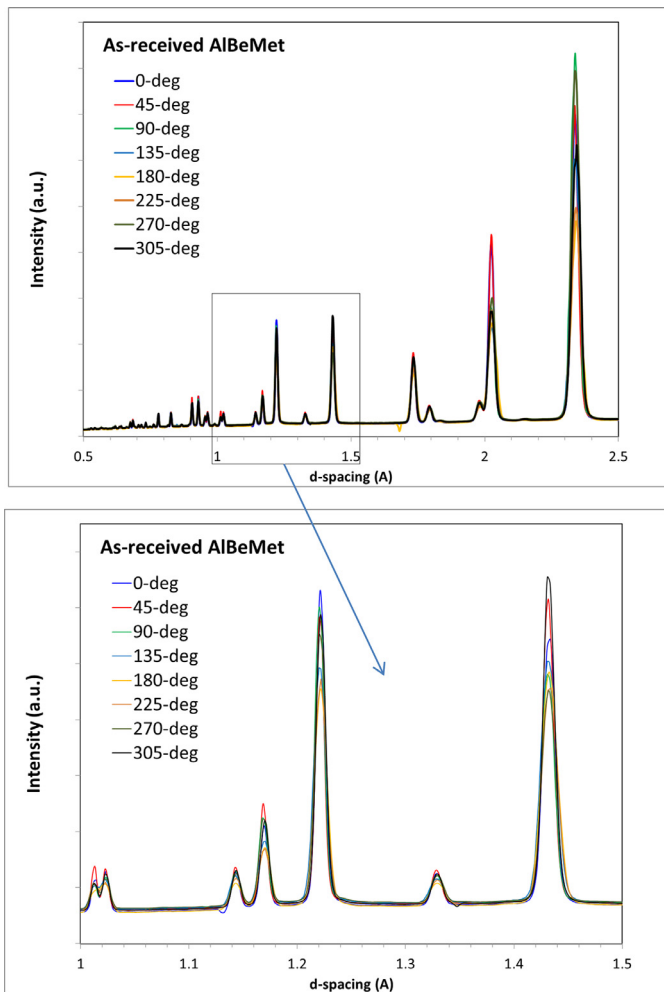


Fig. 10. AlBeMet 162 diffraction pattern and phase identification from 70 keV monochromatic X-rays at NSLS X17A beamline.

in the beryllium part of the matrix and its *hcp* crystal structure where deformation mechanisms such as twinning are possible at specific stress thresholds. Fig. 5(b) shows the effect of increasing proton fluence on the stress–strain behavior of the material. A peak fluence of 1.2×10^{20} p/cm² was achieved during the proton irradiation.

AlBeMet 162 which in the unirradiated state exhibited $\sim 2.4\%$ room temperature elongation has shown remarkable resistance to ductility loss. The yield point of the unirradiated material is only approximately defined and so is that of the proton-irradiated counterparts. It is evident, however, that the yield stress increases, as typically expected with irradiation and AlBeMet 162 is no exception, and so is the ultimate tensile stress. The characteristic deformation “kinks” can also be observed following irradiation accompanied with a stress offset (higher). As shown in Fig. 5(c) where the unirradiated state is compared with excerpt irradiated data one can observe an increase in the Young’s modulus with proton irradiation which does not typically occur in single phase metals.

The thermal stability study of AlBeMet 162, following irradiation with energetic protons, revealed both that material is stable under irradiation and that annealing of induced damage can be realized through thermal cycling. Shown in Fig. 6 is comparison of the linear thermal expansion of AlBeMet 162 to temperatures up to 600 °C between the unirradiated state and different proton fluence levels following irradiation and over the heating phase of the thermal experiment. Shown in the insert is the change in thermal expansion coefficient (CTE) as a function of proton fluence evaluated at 550 °C. As shown, a slight reduction in CTE is observed as a result of energetic proton exposure.

Thermal cycling results up to 600 °C are shown in Figs. 7 and 8. Fig. 7(a) depicts the dimensional change in three thermal cycles in sequence of the test sample receiving an average fluence of 0.6×10^{20} p/cm² and shows the damage annealing evolution with thermal cycling. Specifically, the observed deviation from the unirradiated state during the first cycle to 600 °C is annealed out and during subsequent cycles the irradiated AlBeMet 162 exhibits remarkable stability. Fig. 7(b) is a closer view of the recovery during the first thermal cycle. Swelling that has been induced in the microstructure due to the generation of vacancies and interstitials in the lattice are being thermally activated and anneal out. The level of the deficit of dimensional change shown in Fig. 7b following the first thermal cycle is indicative of the contraction experienced by the irradiated material which is equivalent to the annealed damage or swelling caused by protons.

The irradiation damage resistance to fluence levels up to 0.24×10^{20} p/cm² and the dimensional stability of the irradiated material is shown in Fig. 8 after low temperature thermal cycling (300 °C) and high temperature (HT) thermal cycling to 600 °C. As seen, swelling of AlBeMet 162 caused by proton irradiation to these dose levels is very limited.

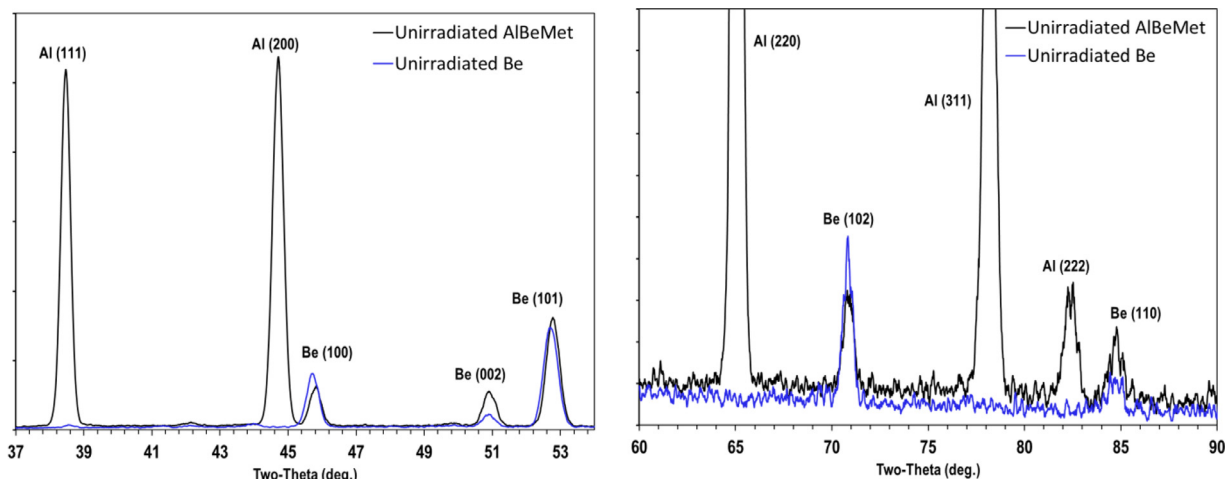


Fig. 11. As received (unirradiated) AlBeMet 162 X-ray diffraction deduced from EDXRD analysis compared with diffraction of Beryllium and demonstrating the complete separation of the two phases which concludes that AlBeMet is a composite.

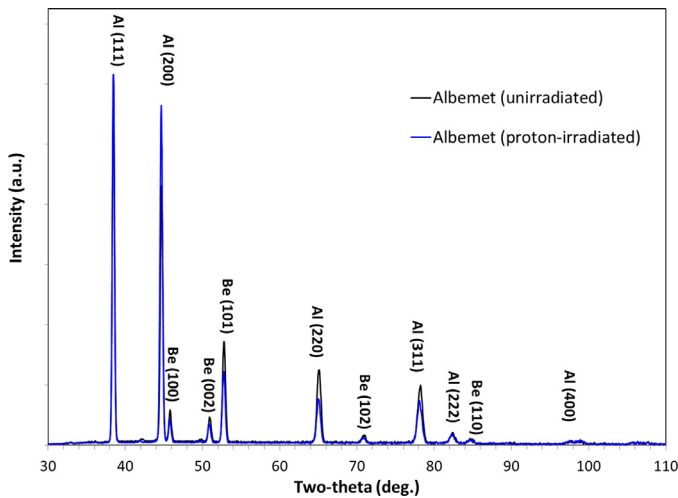


Fig. 12. EDXRD generated diffraction pattern and phase map of unirradiated and proton-irradiated AlBeMet 162.

3.2. Monochromatic X-ray diffraction (X17A experiment)

XRD analysis of unirradiated, as received AlBeMet 162 was conducted at the X17A beamline of NSLS according to Fig. 4(a). The study aimed at evaluating the condition of the binary metal matrix composite, *i.e.* presence of residual strains in the microstructure as a result of fabrication techniques, and the confirmation of the separation of the two phases and finally including isotropy that

the composite exhibits. Fig. 9 depicts the 2-D diffraction patterns obtained in the detector. The state of the microstructure was evaluated by selecting diffraction slices azimuthally which in turn will reveal the presence or absence of residual strains in the lattice (compressive strains appearing on the right hand side of the detector image and tensile on the left hand side). Fig. 10(a) and (b) shows the azimuthally varying XRD patterns of as-received AlBeMet 162 and deduce the following important observations:

- Based on the crystallographic spacing results it is confirmed that the two metal phases (*hcp* beryllium and *fcc* aluminum) remain completely separate and there is no evidence of new phases developing as a result of the process;
- There appears to be no azimuthal variation in crystal plane spacing which is indicative of residual strain free metal matrix prior to irradiation;
- From the complete absence of variability in crystal plane spacing for both metal constituents it can be inferred that AlBeMet 162 exhibits high mechanical isotropy, a property that has been confirmed by the manufacturer via macroscopic testing.

3.3. EDXRD using high energy white X-rays

Using 200 keV white beam X-rays at X17B1 beamline at NSLS unirradiated, as-received AlBeMet 162 tensile samples as well as proton-irradiated, fractured in tension tensile specimens were evaluated. Fig. 11 depicts the phase map of unirradiated (top) and irradiated (bottom) AlBeMet 162 following scanning across the 1 mm thick central part of the gage section of the tensile specimen shown in Fig. 1(b).

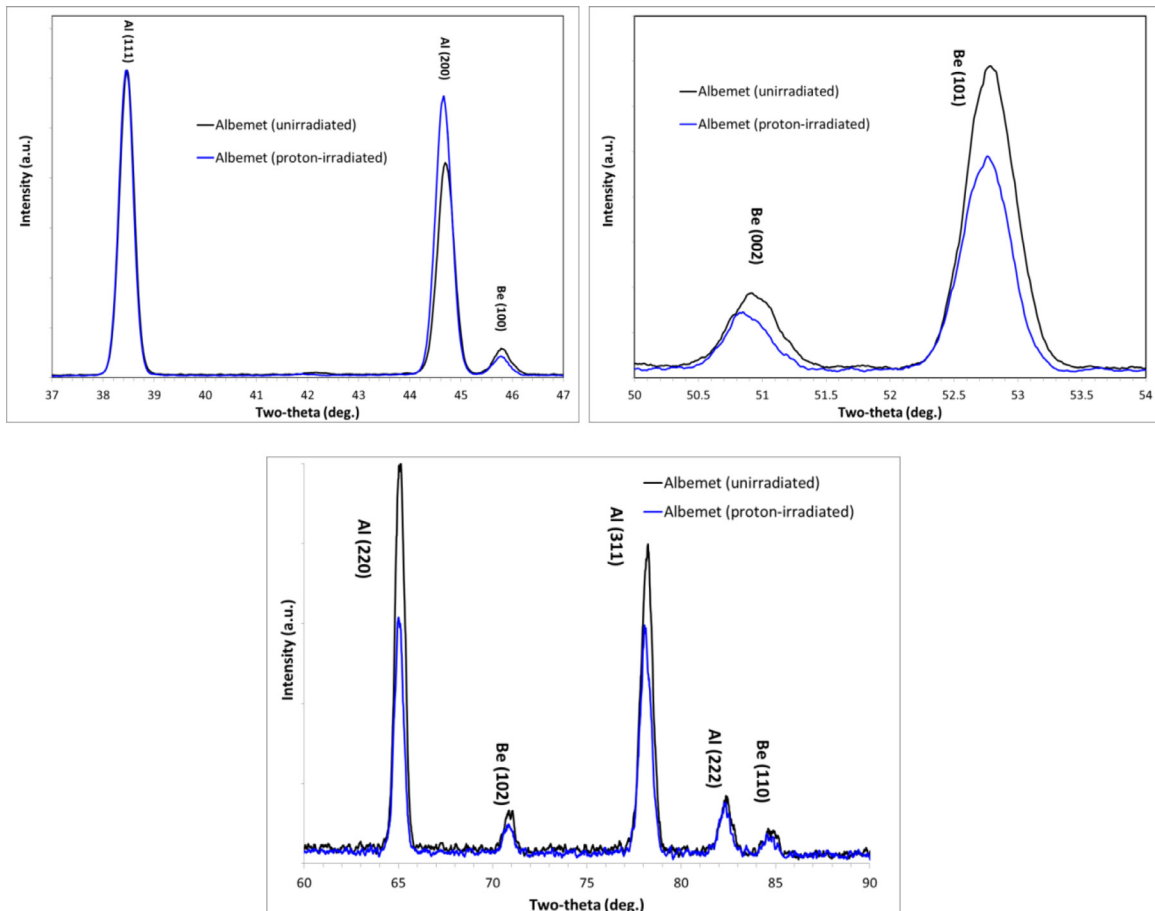


Fig. 13. Proton irradiation effects on the lattice structure of AlBeMet 162.

Fig. 12 shows the phase map of unirradiated and irradiated AlBeMet 162 as obtained by the EDXRD analysis and it confirms the findings of the XRD study using monochromatic X-rays that the phases remain separate. Beyond the experimental error the EDXRD analysis also shows that no phase evolution or appearance occurs as a result of proton irradiation. Examining closer the effects of proton irradiation on the the lattice structure and in particular the changes in crystal plane spacings following irradiation (Fig. 13(a–c)) the following observations are made:

- The (111) plane spacing of the *fcc* aluminum is totally unaffected by proton irradiation which for other planes leads to the formation interstitials and vacancies resulting in an increase of the planar spacing. For *fcc* metals it has been assessed [11] that stacking faults and clusters on the (111) planes are expected to be stable during irradiation and in other words prone to migration away from the cascade region and eventual absorption at various available sinks (dislocations, grain boundaries). This general assessment for *fcc* metals seems to also hold for the *fcc* aluminum phase in AlBeMet where the irradiation-generated interstitials and vacancies appear to be mobile inferred by the observation that the (111) reflection undergoes no inter-plane spacing change.
- The (200) plane spacing of the *fcc* aluminum on the other hand experiences an increase stemming from the presence of interstitials between the (200) planes. It is important to note that no annealing has been applied to these irradiated tensile specimens for interstitials to be thermally activated and return to vacant sites in the lattice.
- The larger change in plane spacing is experienced by the (002) of the *hcp* beryllium which indicates that self interstitials knocked from their lattice position remain between the basal planes of the *hcp* beryllium.
- The diffraction pattern of beryllium phase indicates that the lattice change as a result of irradiation is not a volume conserving process since all the crystallographic spacings in the *hcp* beryllium increase.

The effects of proton fluence on the crystal structure of AlBeMet 162 were explored according to the scanning scheme depicted in Fig. 4(b). Across the gage of the tensile specimen and over the fracture surface there exists a variability in the proton fluence determined by the position and shape of the irradiating beam. Scanning across the gage effectively traverses the Gaussian beam shape ($\sigma = 7.2$ mm) and thus captures both the fluence effect as well as the effect of the plastic deformations developed around the fracture surface. Peak fluence and fracture surface are not coincident due to the fact that proton irradiation has increased the ultimate strength of AlBeMet (see Fig. 5) thus shifting the weakest part of the stress gage towards the lower fluence. Figs. 14 and 15 represent a 3-D phase map along the scanning direction (each diffraction pattern has been offset for clarity). Indicated is the zone of the peak fluence. Most noticeable changes in the crystal structure as a result of increased irradiation is seen in the (102) twinning plane of *hcp* beryllium and the (222) of the *fcc* aluminum.

The diffraction pattern and phase identification deduced from the monochromatic X-ray diffraction of the as-received AlBeMet 162 is shown in Fig. 16. The in-plane φ scans (0–360 degrees) of the representative reflections of the two metal phases, *fcc* aluminum and *hcp* beryllium, are depicted in Fig. 17. As clearly indicated in Fig. 17 the depicted beryllium (101) reflection exhibits no texture and/or preferred orientation (similar observations were made for all Be phase reflections) indicating that Be is the isotropic part of this matrix. On the other hand the three (3) shown reflections of the cubic Al phase showed change in texture with orientation especially the (111) reflection, which exhibited a “non-perfect” six-fold symmetry. The (202) and (200) re-

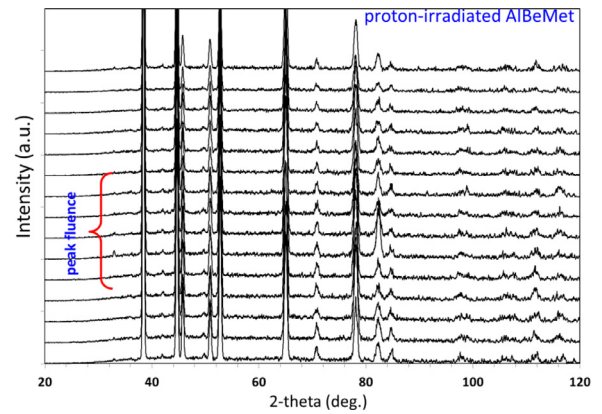


Fig. 14. Diffraction patterns in proton irradiated AlBeMet 162 scanning along the stress gage of the special tensile specimen with varying proton fluence.

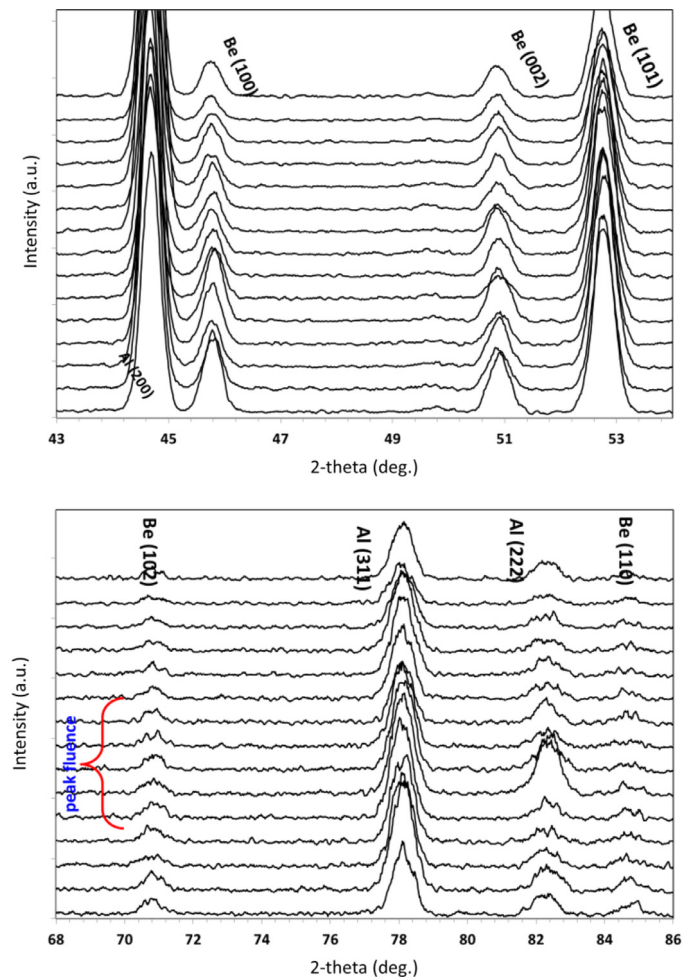


Fig. 15. Proton fluence effects on AlBeMet 162.

lections showed texture effect but less profound than the (111) reflection (Fig. 17). These results don't agree with the manufacture's claim that the matrix is isotropic. The metallic Be phase is isotropic, while the metallic Al phase is textured and (111) reflection is nearly symmetric. As noted following the EDXRD analysis on proton-irradiated AlBeMet Al (111) crystallographic plane showed no change due to irradiation (see Fig. 13a).

The apparent isotropy and lack of texture or preferred orientation in the Beryllium phase of AlBeMet 162 with the concurrent change in texture with orientation and “non-perfect” six-fold

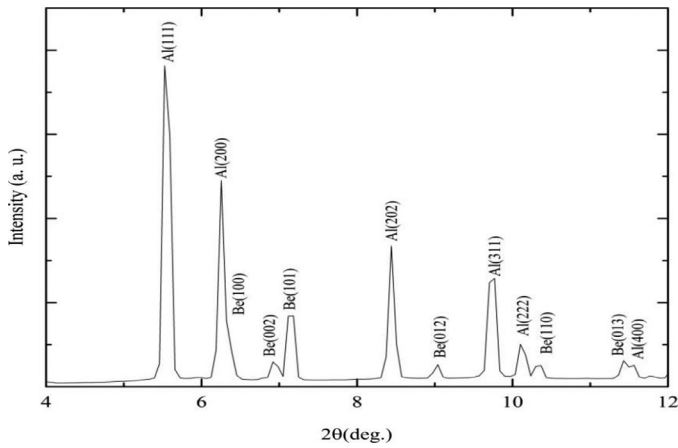


Fig. 16. AlBeMet-162 diffraction pattern and phase identification.

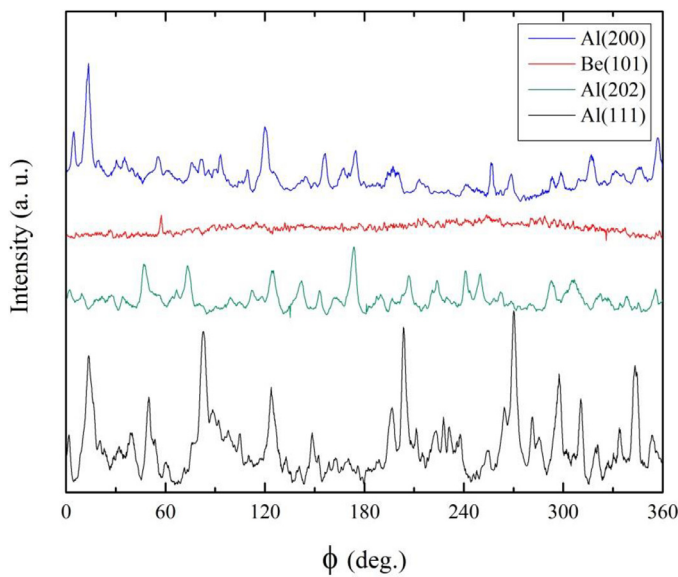


Fig. 17. In-plane ϕ scan of Al (1 1 1), Al (2 0 2), Be (1 0 1), and Al (2 0 0) reflections in the AlBeMet matrix.

symmetry in the Aluminum phase revealed by the monochromatic XRD analysis on unirradiated AlBeMet has been further evaluated using the EDXRD technique while evaluating the irradiation effects on texture and orientation. Fig. 18 depicts the 3-D phase map of unirradiated, as received AlBeMet 162. Shown in Fig. 18 is the intensity variation in all the crystallographic planes of the *fcc* aluminum and the uniformity throughout the scanned volume of the *hcp* Beryllium phase. Fig. 19 shows the 3-D phase map following proton irradiation. As seen in Fig. 19, no reduction of the anisotropy in the *fcc* aluminum results from the proton interaction

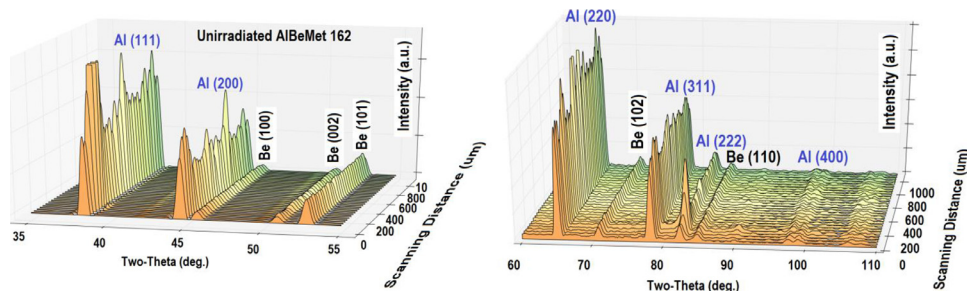


Fig. 18. EDXRD mapping (3D) of phases in unirradiated AlBeMet 162.

is observed. Minimal effects of the irradiating protons on the lattice structure of the *hcp* beryllium phase are observed with more noticeable changes in the twinning plane Be (1 0 2) as shown in Fig. 19(c).

4. Summary and conclusions

The presented study focused on the binary composite AlBeMet 162 (Brush Wellman) consisting of 62% beryllium and 38% aluminum irradiated with 145 MeV protons at the Brookhaven National Laboratory (BNL) Linac to a peak fluence of $\sim 1.2 \times 10^{20} \text{ cm}^{-2}$ and irradiation temperatures in the range of 100–200 °C. Macroscopic and microscopic (X-ray diffraction) post-irradiation analyses were conducted to evaluate the effects of energetic protons on the AlBeMet microstructure and changes in its physio-mechanical properties.

The X-ray diffraction studies were conducted at the BNL NSLS synchrotron X17A and X17B1 beamlines and utilized high energy monochromatic and white beam X-rays (70 keV and 200 keV) by implementing XRD and EDXRD techniques respectively. The objective of these X-ray diffraction analyses was to (a) confirm that AlBeMet 162 is a matrix composite with separate phases (binary) and not an alloy and (b) that following irradiation the composite nature is stable and does not evolve, (c) what crystallographic changes, if any, occur as a result of energetic proton irradiation and how these changes, if distinct, correlate with macroscopically observed irradiation effects.

The multi-faceted PIE study on the proton-irradiated AlBeMet 162 revealed the following:

- Irradiation induces increase in of the ultimate tensile strength and Young's modulus of the binary matrix stemming from pinning of dislocations accompanied by limited loss of the ductility exhibited by the unirradiated material.
- The irradiation damage levels achieved during the irradiation experiment where temperatures in the AlBeMet 162 array ranged between 100 and 200 °C, estimated to be ~ 0.044 DPA for aluminum and 0.01 DPA for beryllium phases respectively, were shown from the X-ray diffraction study to induce limited change in the lattice structure.
- The effect of twinning deformation mechanisms triggered in the *hcp* beryllium is observed macroscopically during tensile tests.
- The matrix is dimensionally stable and the limited irradiation-induced swelling is shown to be reversible upon thermal cycle annealing.
- The X-ray diffraction studies showed that the matrix phases are completely separated prior and after proton irradiation.
- X-ray diffraction studies focusing on the microscopic texture of the composite revealed no texture and/or preferred orientation in the beryllium phase with significant change in texture with orientation in the aluminum *fcc* phase especially the Al (1 1 1) reflection, which exhibited a “non-perfect” six-fold symmetry.

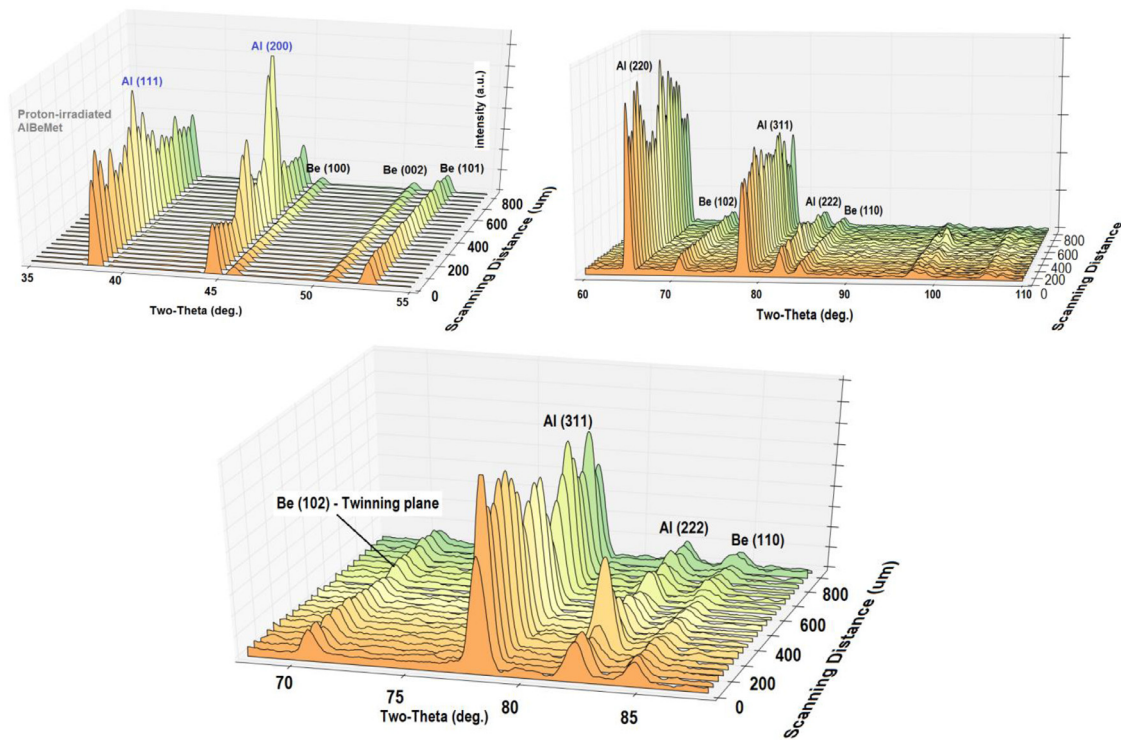


Fig. 19. EDXRD 3D phase mapping of proton-irradiated AlBeMet 162.

While irradiation effects studied and presented in this paper for 140 MeV protons on the two-phase composite interest in neutron effects and damage may be served by extrapolation with extreme caution. Spallation-induced neutrons are contributing to the irradiation mixed spectrum of the current study stemming from proton beam interaction with material upstream of the AlBeMet 162 array but are a 2nd order effect characterized by two orders of magnitude lower fluence compared to the primary irradiating protons. The effects of spallation-induced fast neutrons as the dominant irradiating species on AlBeMet will be evaluated and reported in an upcoming PIE where they will be compared with the effects of energetic protons presented here.

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